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Die amptelike vaktydskrif van die Rekenaarvereeniging van Suid-Afrika en van die Suid-Afrikaanse Instituut van Rekenaarwetenskaplikes

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Editorial

Volume six of QI heralds several changes. The most visible is the change in format. The black on red cover has been changed to a more readable blue on white, but we have retained the style of the old cover, for the sake of continuity. The papers are now set in a tighter format, using double columns, which will enable more papers to be published for the same cost.

For authors, the most significant change is that as from Volume 6 Number 2 (the next issue), a charge will be made for typesetting. The charge is quite modest – R20 per page – and will enable us to keep up the high standards that we have become used to with QI. It is worth recording that the alternative to this suggestion was that authors should present camera-ready typescript, as is done for *Quæstiones Mathematicæ*. Given that document preparation and electronic typesetting is one of the areas of computer science that we can feel proud of, it seemed right that our journal should use the most modern techniques available. Fortunately, the two controlling bodies, the CSSA and SAICS, eventually agreed to our proposal and the result is the professional journal you have in front of you now.

Supporters of QI may be interested in a few statistics that I compiled when I took over the editorship from Gerrit Wiechers in April this year. In the past two years (June 1985 to June 1988), 73 papers have been received. Of these 39 (53%) have appeared, 19 have been rejected or withdrawn (26%) and 15 (21%) are either with authors for changes or with referees. If we look at the complete picture for Volumes 4 and 5, we find the following:

Volume	Issues	Papers	Pages	Ave. pages per paper
5	3	27*	220	7.7
4	3	21	136	6.4

Although this issue contains one very long paper of 18 pages, the future policy of QI will be to restrict papers to 6 or 7 printed pages, and prospective authors are asked to bear this in mind when submitting papers.

For the future, we are hoping to move towards more special issues. Many of the papers being published at the moment were presented at the 4th SA Computer Symposium in 1987. Instead of continuing the policy of allowing such papers to be accepted by QI without further refereeing, we are hoping to negotiate with Conference organisers to produce special issues of QI. Thus the proceedings would *ab initio* be typeset by QI and all the papers would be in a single issue. Given the competitive charges of QI, there will be financial gains for both parties in such an arrangement.

As this is my first editorial, it is fitting that it should close with a tribute to the previous QI team. My predecessor as editor was Gerrit Wiechers. Gerrit took over the editorship in 1980 and served the journal well over the years. With his leadership, the number and quality of the papers increased to its present healthy state. I must also extend a big thank you to Conrad Mueller and the University of the Witwatersrand who pioneered desk top publishing of QI in August 1985, using the IBM mainframe and its laser writer. Without Conrad's diligence and the excellent facilities provided by the Wits Computer Centre and subsequently the Computer Science Department, QI would easily have degenerated into a second-rate magazine. Quintin Gee, also of the Wits Computer Science Department, has taken over from Conrad and has raised the production quality of QI to new heights, as this issue testifies.

I look forward to your help and support in the future. Long live QI!

Judy M Bishop
Editor
June 1988

The Use of Colour in Raster Graphics

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Abstract

Colour computer graphics covers a wide field of applications such as games, computer aided-design, image processing and digital terrain modelling. The traditional way of using colour in raster graphics systems, the RGB colour model, is not always acceptable to the user who finds it unnatural and difficult to use. These disadvantages can be overcome by the use of colour models that provide natural interfaces, such as the HSI, HSL and CNS colour models, or a uniform colour space such as the LUV colour model. This paper describes these models and discusses their use in colour assignment and other applications.

***Keywords:** Colour, colour models, uniform colour spaces, colour in raster graphics.*
***Computing Review Category:** I.3.7.*

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1. Introduction

The use of colour in graphics applications covers a wide field. Colour is used in games, painting programs, computer aided design, educational programs, image processing, digital terrain models (DTM's), and even as a basis for animation [1]. In many applications colour is used to enhance a picture. A typical example of this is the assignment of colours to a grey scale image to accentuate contrasts. In this case the colours should differ as much as possible. In other applications the colour assignment is used to represent some order, for example, heights in digital elevation models.

The way in which colours have to be specified for graphics hardware is not always acceptable to the user. Most colour display units use the three primary colours, red, green and blue, as the basis for the specification of colours. This RBG colour space is not "natural" to the user. For interactive applications a colour model that corresponds more closely to the way in which users think about colour may be preferable. The RGB colour space is also not uniform, that is, colours that are equidistant in the RGB colour space do not appear to be equidistant to the human eye. For example, the human eye can distinguish more shades of green than blue. Applications that use colours to represent a range of values could make good use of a uniform colour space.

Because of the disadvantages of the RGB colour space, several other colour models have been developed. The user specifies a colour by using a particular colour model, and this colour is then converted into RGB and applied to the hardware.

A study of the literature on the use of colour in raster graphics showed the lack of a comprehensive survey of these colour models and their usefulness. This paper attempts to meet this need. Four applicable colour models (in addition to the RGB model) are described and compared, and their use in colour assignment are discussed. The last part of the paper is an extract from an article by G M Murch [2], giving valuable guidelines for the effective use of colour in computer graphics.

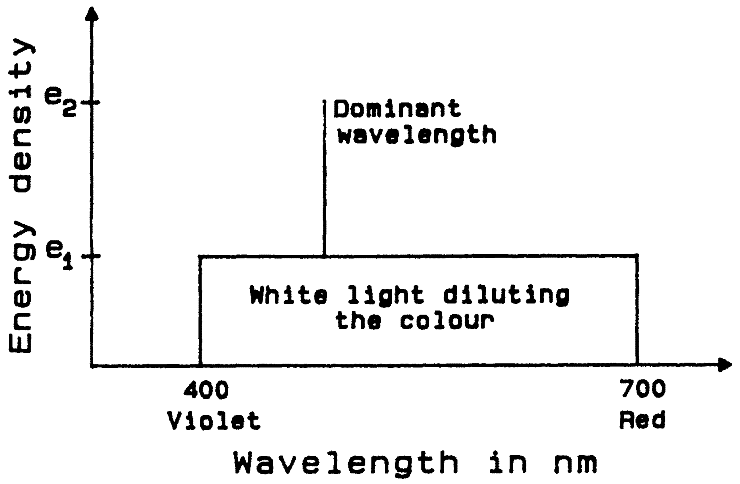
The study on the use of colour was motivated by work done on DTM's in the Computer Science Division of the National Research Institute for Mathematical Sciences, where a library of colour-handling routines was needed for the DTM package. All the colour models presented here were implemented for the Ikonas RD3000 raster graphics system. The routines were written in the SCRAP language [3] and combined in a library called IKSP (Ikonas Support Package) [4].

2. What is Colour?

This section briefly discusses some of the physiological aspects of colour. More detail may be found in [2,5].

2.1 Hue, saturation and brightness

The distinction between chromatic colours such as green and yellow and achromatic colours namely black, grey and white is that chromatic colours have a hue component while achromatic colours have none. **Hue** is the term used to distinguish between colours such as red, blue and yellow, and is an attribute of the wave length of the light rays. **Saturation** (or purity) refers to the extent to which a colour departs from a neutral grey and approaches a pure spectrum colour. A pure colour (that is, one with no white light added) has total saturation, while white light has zero saturation. **Brightness** (also



Hue $= f(\text{dominant wavelength})$

Purity $= f\left(\dfrac{\text{amount of dominant wavelength}}{\text{amount of white light}}\right) = f\left(\dfrac{e_2}{e_1}\right)$

Luminance $= f\left(\begin{matrix}\text{amount of light}\\ \text{or total energy}\end{matrix}\right) = f\left(\begin{matrix}\text{area underneath}\\ \text{the curve}\end{matrix}\right)$

Note: $e_1 = e_2 \Rightarrow \text{purity} = 0\%$
$e_1 = 0 \Rightarrow \text{purity} = 100\%$

Figure 1 Physical interpretation of hue, purity and luminance (adapted from [6])

called **luminance, lightness** or **intensity**) corresponds to the total energy or amount of light in a colour.

In the literature different meanings are attached to the terms lightness, brightness, luminance and intensity. Normally, brightness and lightness refer to objects that are light reflectors, while luminance and intensity are used for light sources. The lightness of an object depends on the amount of light reflected by the object and is a property of the object itself. The brightness of an object depends on the amount of light illuminating the object. If the amount of light illuminating an object is increased, the brightness of the object will increase, but its lightness will stay the same. The luminance of a light source refers to the amount of light energy emitted from the source per unit area, while intensity refers to a hardware function that can be set programmatically or manually.

It must be noted that the terms intensity and lightness used for the HSI and HSL models are used as defined in the descriptions of these models and not in the sense described above. In section 5, **Guidelines for effective colour use**, the other terms for brightness are used as defined above.

2.2 Physiological aspects of colour

The colour seen by human beings is the result of the physical properties of light entering their eyes. The wavelength of visible light ranges from 400 nm (violet) to 700 nm (red). Figure 1 shows the relation between the physical properties of light and the hue, purity and luminance of a colour.

The retina of the human eye contains two types of sensors, called rods and cones. The rods are used for night vision, while the cones contain photopigments that translate light wavelengths into colour sensations. These photopigments are sensitive to red, green or blue light. Because of the variation in the distribution of both photopigments and cones across the retina, we have different response characteristics for each colour (see figure 2) [6]. The combination of these responses results in the sensation of a specific colour.

It is important to note the difference between the colour on a raster graphics display unit and that on a surface such as a painting. The colour display unit uses additive colour mixing, while the colours in a painting are obtained by subtractive colour mixing.

Additive colour mixing starts with black and obtains a colour by mixing coloured lights. Red, green and blue are well known examples of the so-called additive primaries. Their individual contributions are mixed together to form an additive mixture with a certain colour. If the three primaries are mixed together in equal proportions, white light is obtained.

Subtractive colour mixing starts with white light and obtains a colour by subtracting colours from the white light. For example, a piece of paper will be blue if all the colours other than blue are subtracted from the white light illuminating it. Examples of the so-called subtractive primaries are cyan, magenta and yellow, which are the complementary colours to red, green and blue respectively. The relationship

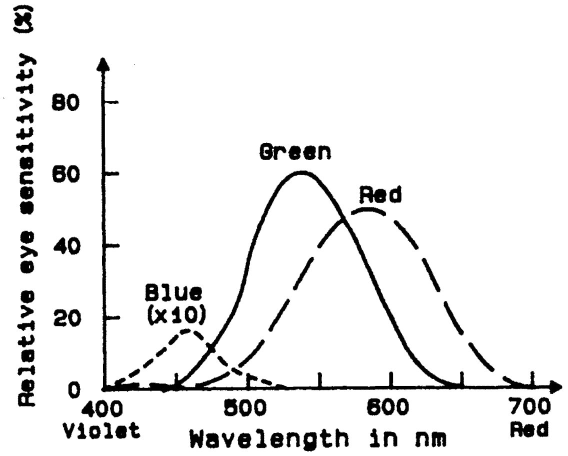


Figure 2 Response characteristics of the human eye (adapted from [6])

between these additive and subtractive primaries can be expressed by

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix} - \begin{bmatrix} C \\ M \\ Y \end{bmatrix}$$

where each primary ranges between 0 and 1. The colours obtained by mixing additive or subtractive primaries are illustrated in figure 3.

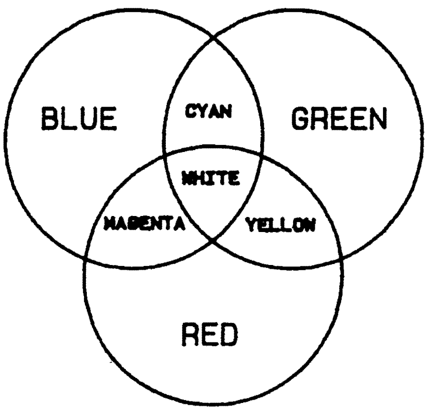


Figure 3a Additive colour mixing with red, green and blue as primaries

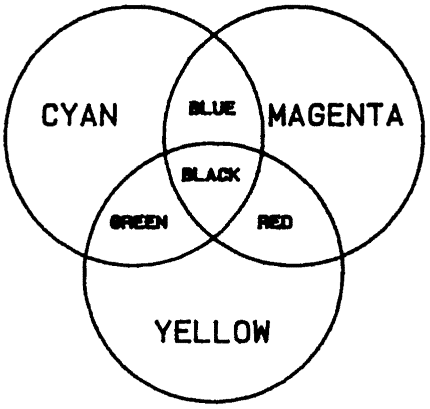


Figure 3b Subtractive colour mixing with cyan, magenta and yellow as primaries

3. Colour Models

In this section the RGB, HSI, HSL, CNS and LUV colour models are outlined and compared. A general description of each model is given, together with the relevant conversion routines and a discussion of the model's use.

It is interesting to note that the HSI conversion routines given here and those given in [6,7,8] are equivalent, although they seem to differ with regard to the definition of hue. The conversion routines for HSL given here and in [6,8,9] are also equivalent (except that [8] differs with regard to the definition for hue). Finally, the seemingly different definitions given by [6] for the hue component of HSI and HSL are identical.

Throughout this section it is assumed that
max = the maximum value of {R,G,B}
mid = the middle value of {R,G,B}
min = the minimum value of {R,G,B}.

3.1 RGB Model

3.1.1 General description

A colour raster graphics display unit is coated with phosphor that emits light when struck by the electron beam of the display unit. Three different types of phosphor, each emitting one of the three primary colours, are used. These primary colours, red, green and blue, (R,G,B) can be combined with positive weights to obtain a large range of colours. However, some visible colours cannot be defined in terms of positive weights for the (R,G,B) primaries. This is why the Commission Internationale L'Eclairage (CIE) in 1931 defined the three primary colours (X,Y,Z) as the international standard for specifying colour (see [5]). These primaries can be combined with positive weights to define all the light sensations that we perceive with our eyes.

The geometric model associated with the RGB model is a cube (see figure 4) with a primary along each of the three axes. The value of each primary ranges between 0 and 1. The nine corners of the cube correspond to black, white, the three additive primaries, and the three subtractive primaries.

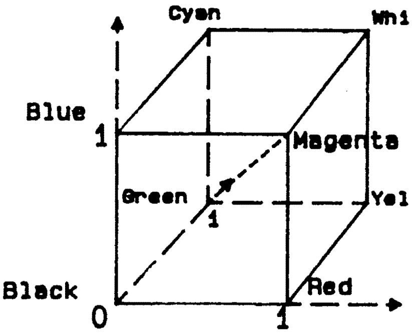


Figure 4 The RGB colour cube

3.1.2 Converting between XYZ and RGB

A set of routines is needed to convert between the (X,Y,Z) primaries of the CIE and the (R,G,B) primaries of colour display units.

LET

P = matrix of chromaticities of phosphors used in the display unit

$$= \begin{bmatrix} x_r & x_g & x_b \\ y_r & y_g & y_b \\ 1-(x_r+y_r) & 1-(x_g+y_g) & 1-(x_b+y_b) \end{bmatrix}$$

P^{-1} = inverse of matrix P

$$V = \begin{bmatrix} X_0 \\ Y_0 \\ Z_0 \end{bmatrix} = \text{vector of tristimulus values of CIE standard illuminant divided by 100}$$

$$\begin{bmatrix} c_r \\ c_g \\ c_b \end{bmatrix} = P^{-1}V$$

THEN

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = P \begin{bmatrix} c_rR \\ c_gG \\ c_bB \end{bmatrix}$$

$$\begin{aligned} X &= c_rx_rR + c_gx_gG + c_bx_bB \\ \text{giving } Y &= c_ry_rR + c_gy_gG + c_by_bB \\ Z &= c_rz_rR + c_gz_gG + c_bz_bB \end{aligned}$$

The value of P depends on the colour display unit (see [5] for more detail). The standard for chromaticities of colour television were set by the U.S. National Television System Committee (NTSC) in 1953. According to this standard,

$$P = P1 = \begin{bmatrix} 0.67 & 0.21 & 0.14 \\ 0.33 & 0.71 & 0.08 \\ 0.00 & 0.08 & 0.78 \end{bmatrix}$$

However, the chromaticities of the phosphors now commonly used in colour television deviate somewhat from the NTSC standard:

$$P = P2 = \begin{bmatrix} 0.68 & 0.28 & 0.15 \\ 0.32 & 0.60 & 0.07 \\ 0.00 & 0.12 & 0.78 \end{bmatrix}$$

The values used for the vector V depend on the light source illuminating the colour display unit. Normally, this is taken as one of the CIE standard light sources corresponding to average daylight, namely C or D65. The current standard practice is to use the D65 standard illuminant. Tables of the so-called tristimulus values for CIE standard illuminants are given in [5] for the CIE 1931 Standard Colorimetric Observer and for the CIE 1964 Supplementary Standard Colorimetric Observer. Preference should be given to the 1964 data when areas of the same colour are large (that is, more than 2 cm in diameter). The 1931 data are more suitable for smaller colour areas (that is, less than 2 cm in diameter). See [5] for a detailed discussion of standard light sources.

The tristimulus values, divided by 100, of the C and D65 standard illuminants are as follows.

$$V = V1 = \begin{bmatrix} 0.98041 \\ 1.0 \\ 1.18103 \end{bmatrix}, \quad V = V2 = \begin{bmatrix} 0.95017 \\ 1.0 \\ 1.08813 \end{bmatrix}$$

C Illuminant
1931 Observer

D65 Illuminant
1931 Observer

$$V = V3 = \begin{bmatrix} 0.97298 \\ 1.0 \\ 1.16137 \end{bmatrix}, \quad V = V4 = \begin{bmatrix} 0.94825 \\ 1.0 \\ 1.07381 \end{bmatrix}$$

C Illuminant
1964 Observer

D65 Illuminant
1964 Observer

If the second set of values for P (P = P2) is used, as well as the 1964 data for D65 (V = V4), the following is obtained:

$$\begin{aligned} X &= 0.437509R + 0.331566G + 0.179175B \\ Y &= 0.205887R + 0.710498G + 0.0836149B \\ Z &= 0.1421G + 0.931709B \end{aligned}$$

The inverse transformation is given by

$$\begin{aligned} R &= 2.87574X - 1.25391Y - 0.440496Z \\ G &= -0.848557X + 1.80318Y + 0.00135981Z \\ B &= 0.129418X - 0.275013Y + 1.07309Z \end{aligned}$$

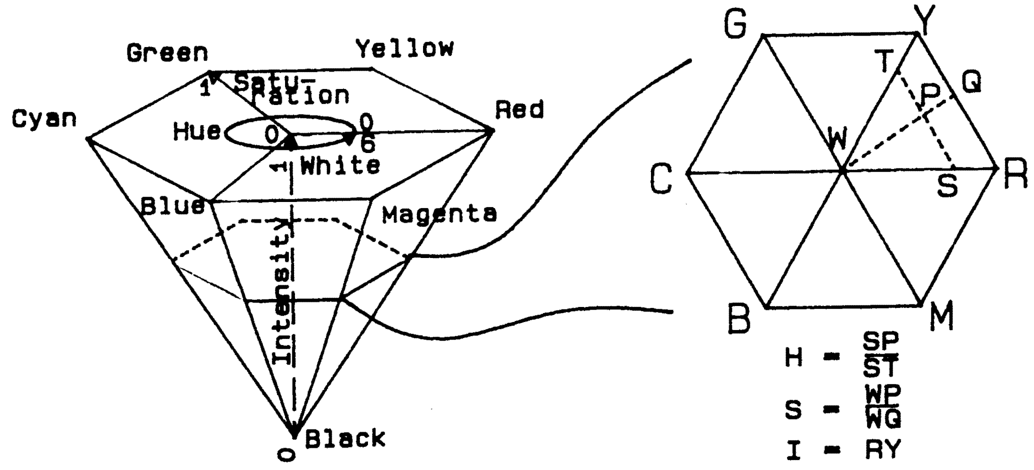


Figure 5 The HSI colour model. H, S, and I are defined using the geometric model

3.1.3 Use of the RGB model

The shortcomings of the RGB colour model, namely its lack of naturalness and uniformity, have already been mentioned.

However, many applications still use this model. The RGB model, being hardware oriented, needs no time-consuming conversions. Furthermore, there is a considerable amount of knowledge available on the eye's response and sensitivity to colours specified as (R,G,B) triples. In some instances interpolation done in RGB space may still be preferred. For example, the shadow series for a colour illuminated by a single light source is determined by linear interpolation between the particular colour and black in RGB space [8].

3.2 HSI Model

3.2.1 General description

The HSI (hue, saturation and intensity) model [6,7,8] is intended to appear more natural to the user, as it is based on the intuitive appeal of tint, shade and tone used by the artist. In the literature different names are used for the three components, but here the terms hue, saturation and intensity are used.

The subspace within which the colour model is defined is a hexcone (figure 5). A formal derivation of the model can be found in [7]. Only a general description is given here.

The vertical axis represents the intensity of the colour, where intensity may be seen as the distance from black. On the vertical axis itself the colour will be achromatic, going from black (at I = 0) through grey to white (at I = 1). The hexcone is defined such that the length of a side of a hexagon disk (RY, for example) is the same as the value of I for that disk.

The saturation (S) of a colour is defined as a ratio depending on the horizontal distance from the vertical axis of the hexcone. In figure 5 the saturation of the colour at P will be the ratio WP/WQ. The value of S is 0 at the vertical axis and 1 on the triangular sides of the hexcone.

The third component defining a colour is its hue. In the hexcone model the hue depends on the angle around the vertical axis, starting at red and moving in an anticlockwise direction (by convention). The hue value ranges between 0 (which is red) and 6 (which is again red). In figure 5 the hue of the colour at P will be the ratio SP/ST.

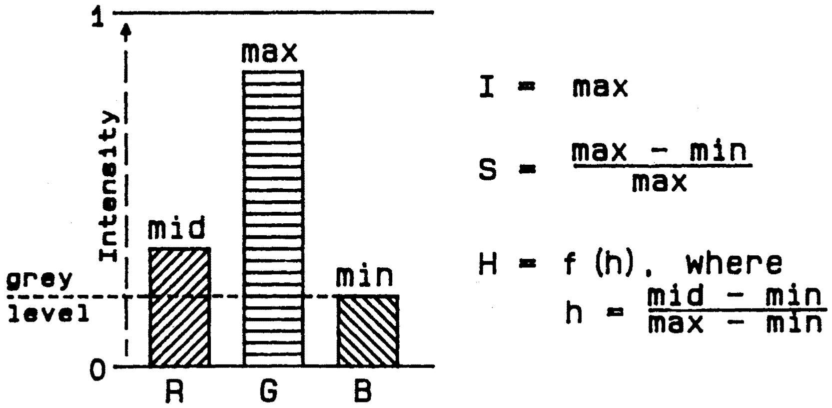


Figure 6 Bar representation of colour components and their relation to hue (H), saturation (S) and intensity (I)

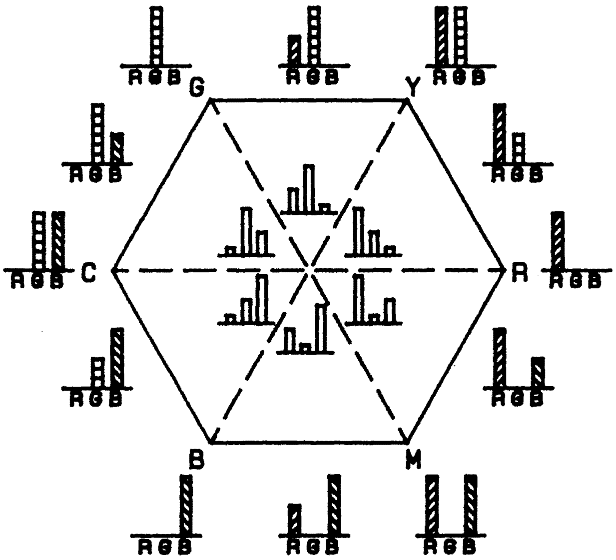
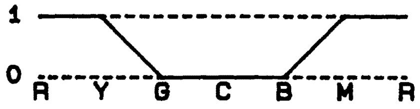
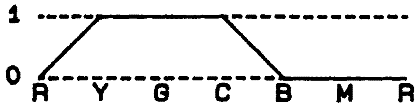


Fig 7

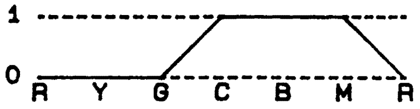
HSI colour hexagon showing the R-G-B ratios.The pure colours are on the circumference and the desaturated colours within the hexagon.



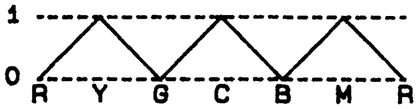
(i) Red



(ii) Green



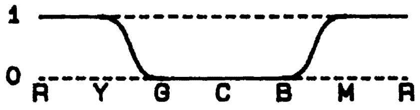
(iii) Blue



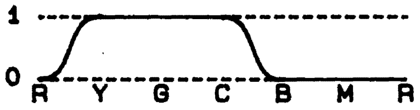
(iv) Hue ratio (h)

Linear variation of the hue components and the hue ratio (h).

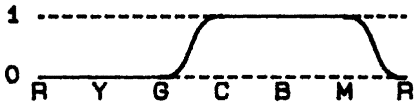
Fig 8a



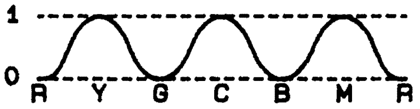
(i) Red



(ii) Green



(iii) Blue



(iv) Hue ratio (h')

Sinusoidal variation of the hue components and the hue ratio (h'), using $h' = (1 - \cos(\pi h))/2$

Fig 8b

3.2.2 RGB to HSI conversion

In the RGB colour space a colour can be represented by three bars (figure 6). The colour is obtained by mixing R, G and B in the proportions implied by the height of the three bars. The intensity (I) of the colour is then defined as the height of the bar: I = max.

The height of the smallest bar is min, and the RGB triple (min, min, min) is the grey which desaturates the colour. The saturation of the colour is defined as the ratio of the non-grey part of the colour to its whole:

S = (max – min)/max. For the case where R = G = B = 0, S is also defined to be 0.

Subtraction of the grey level (min, min, min) from the colour leads to the observation that a hue is determined by two primary colours only, namely the maximum and middle values of R, G and B. Hue H therefore depends on the ratio h, where h = (mid – min)/(max – min).

In the hexcone model, the hue is a modular function, cycling through red, yellow, green, cyan, blue and magenta. This must be mapped onto a hexagon plane of the hexcone model. Figure 7 shows how the R, G and B components vary in the different sectants. The change in value for each component is given separately in figure 8a. The hue ratio h, which oscillates between 0 and 1, is also depicted.

The hue of a colour is defined as a different function of h for each sectant (see figure 9). Thus the value of H ranges between 0 and 6. Because this function is noncontinuous and the human system tends to enhance these variations, a hue series will exhibit Mach banding. This may be overcome by using a sinusoidal function h', where h' = (1 – cos(πh))/2 [8]. Figure 8b shows the values of each component when this function is used.

Segment	Hue ratio (h)	Definition of Hue (H)	Range of H
R-Y	0 - 1	h	0 - 1
Y-G	1 - 0	2 – h	1 - 2
G-C	0 - 1	2 + h	2 - 3
C-B	1 - 0	4 – h	3 - 4
B-M	0 - 1	4 + h	4 - 5
M-R	1 - 0	6 – h	5 - 6

Figure 9 Definition of the hue component (H) in terms of the hue ratio (h)

If S = 0 (that is, max = min), the value of H is undefined. For practical purposes, however, H is set to 0 (red) whenever S = 0. This gives us the following:

GIVEN: R, G, and B, each in [0, 1]
DESIRED: H in [0, 6), S and I in [0, 1]
FORMULA:
I = max

$$S = \begin{cases} \dfrac{\max - \min}{\max} & \text{if } \max \neq 0 \\ 0 & \text{if } \max = 0 \end{cases}$$

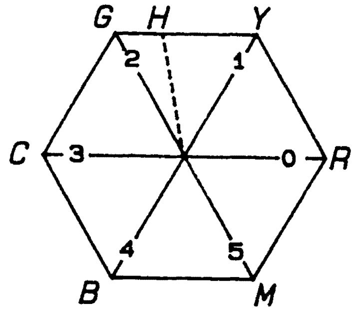
$$H = \begin{cases} 0 & \text{if } S = 0 \\ h & \text{if } R \geq G \geq B \\ 2 - h & \text{if } G > R \geq B \\ 2 + h & \text{if } G \geq B > R \\ 4 - h & \text{if } B > G > R \\ 4 + h & \text{if } B > R \geq G \\ 6 - h & \text{if } R \geq B > G \end{cases}$$

where

$$h = \begin{cases} \dfrac{\text{mid} - \min}{\max - \min} & \text{if linear hue variation} \\ \dfrac{1}{2}\left[1 - \cos\left(\pi\dfrac{\text{mid} - \min}{\max - \min}\right)\right] & \\ \text{if sinusoidal hue variation} & \end{cases}$$

3.2.3 HSI to RGB conversion

This is simply the inverse of the RGB to HSI conversion.



GIVEN: H in [0, 6), S and I in [0, 1]
DESIRED: R, G, and B, each in [0, 1]
FORMULA:
max = I
min = max (1 – S)
mid = min + fract(max – min)
where

$$\text{fract} = \frac{\text{distance from nearest primary (e.g. } GH)}{\text{length of segment (e.g. } GY)}$$

$$= \begin{cases} h = \text{ABS}\left(2\left\lfloor \dfrac{H}{2} + \dfrac{1}{2}\right\rfloor - H\right) & \\ \qquad \text{if linear hue variation} & \\ \dfrac{1}{\pi}\arccos(1 - 2 \times h) & \\ \qquad \text{if sinusoidal hue variation} & \end{cases}$$

SELECT $\lfloor H \rfloor$ FROM
CASE 0: (R,G,B) ← (max, mid, min) {*RY*}
CASE 1: (R,G,B) ← (mid, max, min) {*YG*}
CASE 2: (R,G,B) ← (min, max, mid) {*GC*}
CASE 3: (R,G,B) ← (min, mid, max) {*CB*}
CASE 4: (R,G,B) ← (mid, min, max) {*BM*}
CASE 5: (R,G,B) ← (max, min, mid) {*MR*}
ENDS

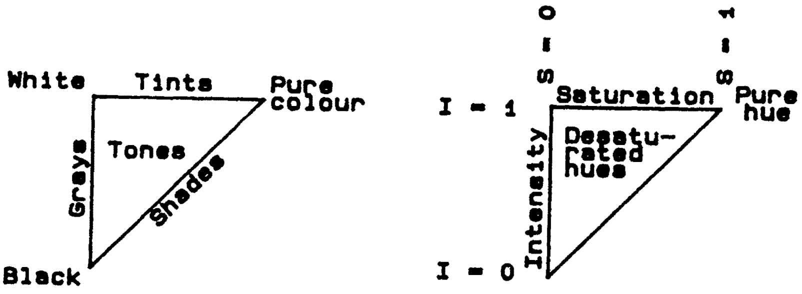


Figure 10 Correspondence between the artist's tint, tone and shade and the HSI model's hue, saturation and intensity

3.2.4 Use of the HSI model

When implemented, the routines to convert between HSI and RGB must make provision for the fact that most hardware requires non-negative integer parameters. As the use of integers causes a loss of accuracy, a conversion from RGB to HSI and back to RGB will not always return the same RGB values. However, the resolution of the hardware is normally such that this error is invisible to the human eye.

It must also be noted that, because of the nature of the HSI model, more than one HSI value will be mapped onto the same RGB value. On the other hand, this RGB value will be mapped onto one HSI value only. The convention that H = 0 when S = 0 may be changed to fit the application [7].

The biggest advantage of the HSI model is its intuitive appeal to the user. The correspondence between hue, saturation and intensity and the artist's use of tint, shade and tone (see figure 10) makes the HSI model very suitable for painting on a raster screen. This model has also been used in a program teaching colour theory to art students [10].

In [7,11], an example of so-called "tint painting" is given. Here the "tint" (hue and saturation) of a picture is changed, but the grey level (intensity) is to stay the same. This is done by the conversion of the RGB values of the pixels underneath the "paint brush" to HSI and the extraction of their I values. These I values are then combined with the H and S of the new tint and converted to obtain a new RGB value for the pixels.

From the tint painting example it is clear that the conversion must be fast. To this end HSI is very suitable, because it is possible to do the conversion without using floating point arithmetic.

In the HSI model the pure, maximally saturated hues are at S = 1 and I = 1. This is an advantage (when compared with HSL) if potentiometers are used to specify the colour model parameters.

A disadvantage of the HSI model is that it is not possible to go, for example, from black through dark green, green and light green to white by changing only one parameter (as can be done with HSL). Both S and I have to be changed. An advantage (over RGB, for example) is that it is possible to go through all the hues at a certain saturation and intensity by changing only the value of H.

The HSI colour model is not a uniform colour space. Colours that are equidistant in the model are not necessarily perceived as being equidistant by the human eye. This is especially noticeable in the green region of the colour space.

The sinusoidal hue variation attempts to improve the uniformity of the hue component. The effect of the sinusoidal function is that the hues are placed nearer to one another at the red, yellow, green, cyan, blue and magenta regions, and spaced wider in the red-yellow, yellow-green, green-cyan, cyan-blue, blue-magenta and magenta-red regions. However, whether one compares the distances in the uniform LUV colour space or the visual results, there does not seem to be a real improvement.

When interpolation between two colours in a colour space is done, the intermediate points differ for each colour space. In some instances of interpolation, the HSI colour space may be preferred [8]. Interpolating between a colour and an unsaturated blue in HSI simulates the effect of atmospheric scattering more closely than similar interpolation in (say) RGB [12]. HSI allows one to keep the saturation and intensity constant while interpolation is done between two hues, whereas this is difficult to achieve in RGB space.

The HSI model can be used for colour assignment [13] and will give better results than the RGB model in most cases. In 4.2 this topic is discussed further.

3.3. HSL Model

3.3.1 General description

The HSL (hue, saturation, lightness) colour model [6,8,9] is used by Tektronix Inc., and is similar to the HSI model. Lightness (L) is defined in such a way that it is possible to go from black through green to white by only changing the value of L.

The HSL has a double hexcone as colour subspace. The hexcone of the HSI colour model is deformed into a double hexcone by "pulling" the white upwards (see figure 11). The representation of hue and saturation in the hexcone is the same as in the

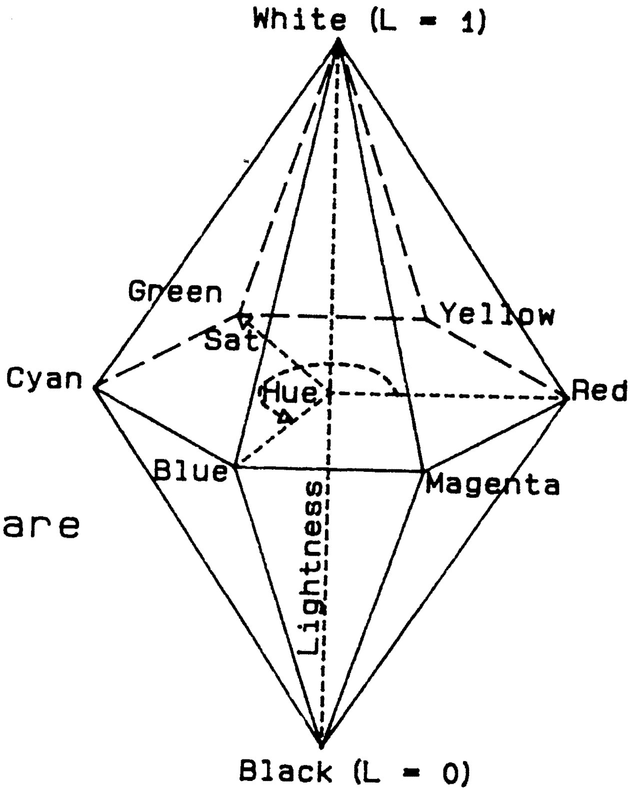


Fig 11

HSL colour model. The pure colours are at L = 0.5.

HSI model. The lightness is still represented by the vertical axis, with black at L = 0 and white at L = 1, but the fully saturated colours are at L = 0.5. Note that a fully saturated colour at L = 0.5 and S = 1 in the HSL model will have I = 1 (not I = 0.5) and S = 1 in the HSI model.

3.3.2 RGB to HSL conversion

In the HSL colour model the definition of the hue of a colour is exactly the same as in the HSI colour model. As stated above, the definition of L is changed (from the definition of I) to form a double hexcone. The definition of S is adjusted accordingly.

GIVEN: R, G, and B, each in [0, 1]

DESIRED: H in [0, 6), S and L in [0, 1]

FORMULA:

$$L = \frac{\max + \min}{2}$$

$$S = \begin{cases} \dfrac{\max - \min}{\max + \min} & \text{if } L \leq 0.5 \\ \dfrac{\max - \min}{2 - \max - \min} & \text{if } L > 0.5 \\ 0 & \text{if } L = 0 \text{ or } L = 1 \end{cases}$$

$$H = \begin{cases} 0 & \text{if } S = 0 \\ h & \text{if } R \geq G \geq B \\ 2 - h & \text{if } G > R \geq B \\ 2 + h & \text{if } G \geq B > R \\ 4 - h & \text{if } B > G > R \\ 4 + h & \text{if } B > R \geq G \\ 6 - h & \text{if } R \geq B > G \end{cases}$$

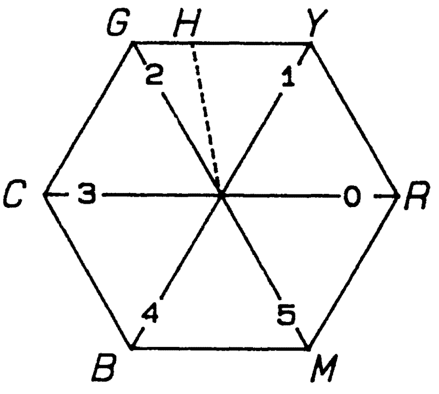
where

$$h = \begin{cases} \dfrac{\text{mid} - \min}{\max - \min} & \text{if linear hue variation} \\ \dfrac{1}{2}\left[1 - \cos\left(\pi \dfrac{\text{mid} - \min}{\max - \min}\right)\right] & \\ \text{if sinusoidal hue variation} & \end{cases}$$

Note that L is now halfway between max and min. The denominator of S therefore includes both max and min (in contrast to the HSI definition of S). If S = 1 on the lower half of the hexcone (L < 0.5), at least one of R, G or B is 0. If S = 1 on the upper half of the hexcone (L > 0.5), at least one of R, G or B is 1.

3.3.3 HSL to RGB conversion

This is simply the inverse of the RGB to HSL conversion.



```
GIVEN: H in [0, 6), S and L in [0, 1]
DESIRED: R, G, and B, each in [0, 1]
FORMULA:
max = L + L × S                  if L ≤ 0.5
      L + S − L × S              if L > 0.5
min = 2 × L − max
mid = min + fract(max − min)
where
$\text{fract} = \frac{\text{distance from nearest primary (e.g. } GH)}{\text{length of segment (e.g. } GY)}$
    $= \begin{cases} h = \mathrm{ABS}\left(2\left\lfloor \frac{H}{2} + \frac{1}{2} \right\rfloor - H\right) & \text{if linear hue variation} \\ \frac{1}{\pi}\arccos(1 - 2 \times h) & \text{if sinusoidal hue variation} \end{cases}$
SELECT ⌊H⌋ FROM
    CASE 0:  (R,G,B) ← (max, mid, min)    {RY}
    CASE 1:  (R,G,B) ← (mid, max, min)    {YG}
    CASE 2:  (R,G,B) ← (min, max, mid)    {GC}
    CASE 3:  (R,G,B) ← (min, mid, max)    {CB}
    CASE 4:  (R,G,B) ← (mid, min, max)    {BM}
    CASE 5:  (R,G,B) ← (max, min, mid)    {MR}
ENDS
```

3.3.4 Use of the HSL model

The HSL conversion routines have the same accuracy problems as the HSI routines when integer parameters are used. Also more than one HSL value is mapped onto the same RGB value. As with HSI, the convention that H = 0 when S = 0 can be changed to fit the application.

The advantage of the HSL model (as with HSI) is its intuitive appeal to the user. It has the "natural" components of hue, saturation and lightness. An improvement on HSI is that a given tint (a H and S value) can be varied from almost black to almost white by only the L value being changed. This corresponds to our natural colour language, since we talk of dark green, green and light green. This is probably the reason why the HSL model is used by Tektronix and the CORE system [9]. For the same reason the HSL model is used as the basis of the CNS model, where colour is specified in natural language (see 3.4).

The HSL model can be used in painting routines in a way similar to the HSI model. A picture may be "painted" darker or lighter by only the L value being changed. The RGB value of a pixel underneath the paint brush is converted to HSL, the L value is replaced by the L value of the paint and the pixel is given the corresponding new RGB value. The speed of this operation should be adequate because the HSL conversion is simple and straightforward.

The advantage of the HSL model can also be a disadvantage. In some applications it would be better if the fully saturated hues were at L = 1 and not at L = 0.5. An example is when potentiometers are used to specify the parameters of HSL.

The hue component in HSL and HSI is exactly the same. The sinusoidal hue variation effects no noticeable improvement, while interpolation that keeps the saturation and lightness constant and only changes the hue is possible. Colour assignment (see 4.3) can be done in a similar way as for the HSI model.

The HSL colour space is not a uniform colour space. Uniform steps in L, for example, do not appear to be uniform to the human eye.

3.4. CNS Model

3.4.1 General description

The Colour Naming System (CNS) is not a colour model in its own right, but a naming system built upon the HSL colour model [14]. It allows the specification of colours by use of their "natural" English names. A common English term is used to describe each of the lightness, saturation and hue components of a colour.

There are five possibilities for the lightness component, namely **very dark**, **dark**, **medium**, **light** and **very light**. If this component is not specified, **medium** is used. Four saturation levels are possible, namely **greyish**, **moderate**, **strong** and **vivid**, with **vivid** being the default term.

Hue names are formed from seven generic hues, namely **red**, **orange**, **brown**, **yellow**, **green**, **blue** and **purple**. These terms, together with **black**, **white** and **grey** constitute the basic colour terms in English; **pink** is specified as **light red**, which is easily understood. Chromatic hue names are formed by the combination of the generic hue names that are adjacent on the HSL hue circle. 'Half-way' hues (for example, **yellow-green**) or 'quarter-way' hues (for example **yellowish green**) may be formed. The yellow-green hue will be half-way between yellow and green on the hue circle and yellowish green will be half-way between yellow-green and green.

Achromatic hue names are formed by black, white and grey, the latter being formed together with a lightness term (for example, light grey). Figures 12 and 13 illustrate the syntax of the CNS model.

3.4.2 CNS to RGB conversion

A colour specified in CNS notation is first converted to HSL, and then the HSL to RGB conversion routine is used. The conversion to HSL is done by the mapping of the CNS lightness and saturation terms onto corresponding L and S values of the HSL colour model. Similarly, the CNS generic hues are mapped onto corresponding H values of the model. The 'half-way' and 'quarter-way' hues are mapped onto H values half-way and quarter-way between the generic hues as shown in figure 13.

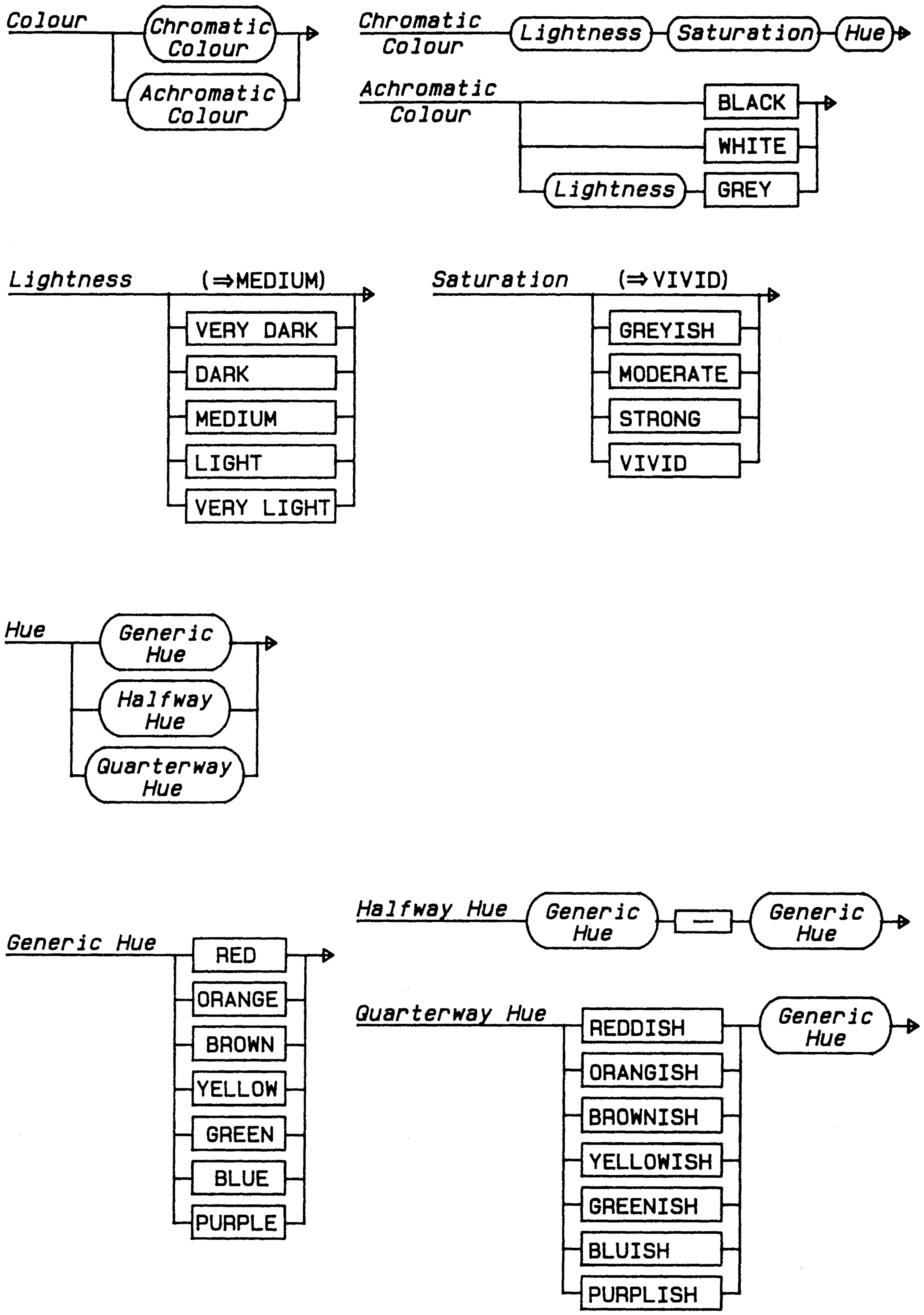
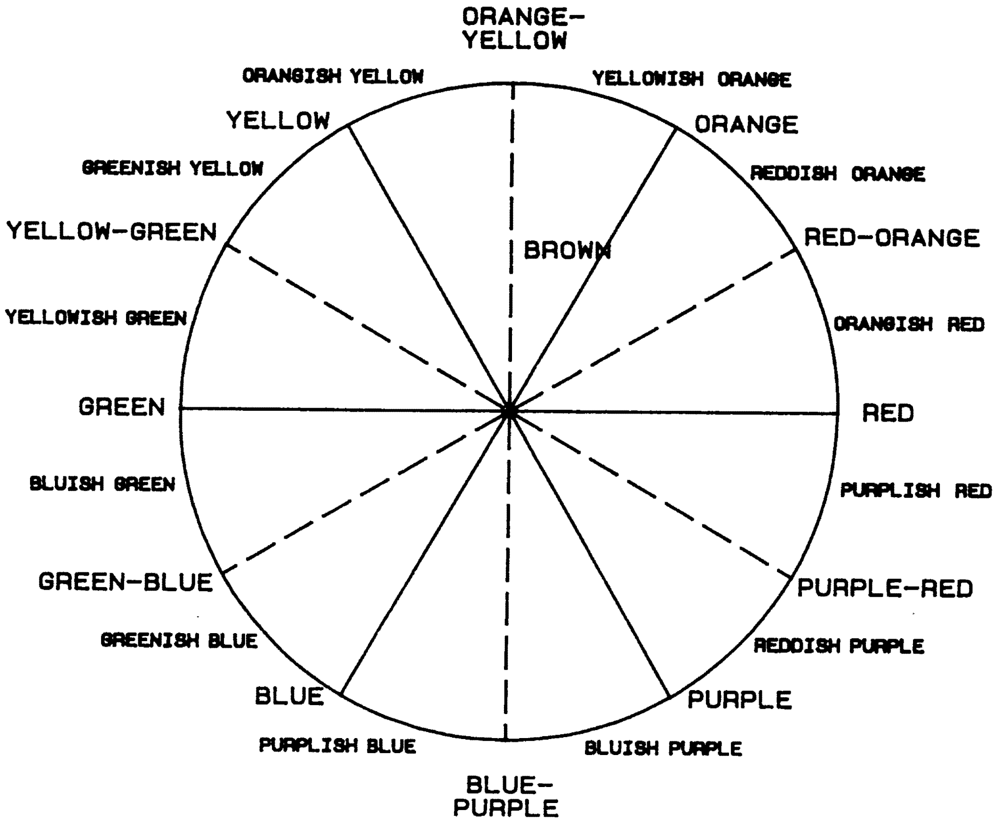


Fig 12 CNS syntax



(a) Chromatic hue names

GREEN
LIGHT BLUE
LIGHT MODERATE GREEN
REDDISH ORANGE
VERY LIGHT VIVID BLUE-PURPLE
BLACK
DARK GREY

(b) Examples

Fig 13 CNS syntax examples

3.4.3 RGB to CNS conversion

The conversion from RGB to CNS is the inverse of the CNS to RGB conversion. First a conversion from RGB to HSL and then a mapping from HSL to the CNS syntax is done. Because of the coarse resolution of CNS, many HSL colours will be mapped onto the same CNS colour as, for example, only five terms for lightness are possible in CNS. If a value is between two terms, the term that is the nearest to the actual value is selected.

3.4.4 Use of the CNS Model

The advantage of the CNS model is the ease with which it can be used. Colours are specified by using their English names and not by giving numeric values. The disadvantage is the coarse resolution imposed by the limited number of English terms used. In spite of this coarse resolution, a study has shown the superiority of the CNS model over the RGB and HSI models in the identification of colours [14].

As soon as the user requires a finer resolution for the specification of colours, the CNS model is unable to cope. A solution is to use the HSL model for finer resolution, since the CNS model uses the HSL model as basis. It remains difficult, however, to specify a range of colours in CNS (for example, all the colours from dark green to light green). This shows that the CNS model's use is limited to the specification and/or identification of one colour at a time.

Another disadvantage of the CNS model is in its implementation. It is difficult to calibrate the model, that is, to specify the values to be used for all the lightness and saturation terms and for brown. For example, a set of lightness values that is acceptable for green is not necessarily acceptable for blue.

3.5. LUV Model

3.5.1 General description

The LUV colour model [5,15,17] differs from the other colour models in that it is not intended to make colour specification more "natural" to the user. Its aim is rather to provide a uniform colour space, by which is meant a colour space in which differences in the human perception of colours correspond approximately to Euclidean distances.

The LUV model (see figure 14) was developed on an experimental basis and does not have a straightforward natural interpretation such as the HSI model. Its three components are called L, U and V. L gives the luminance of a colour and is similar to I of HSI and L of HSL. The U component gives the chromaticity variation approximately from green to red, and V gives the chromaticity variation approximately from blue to yellow.

For the LUV colour space to appear to be uniform to the human visual system, environmental factors, such as the phosphors used for the colour display unit and the properties of the light source illuminating the display unit, must be taken into account. Since this is a science in itself, only the formulas used are given here. Reference [5] gives an

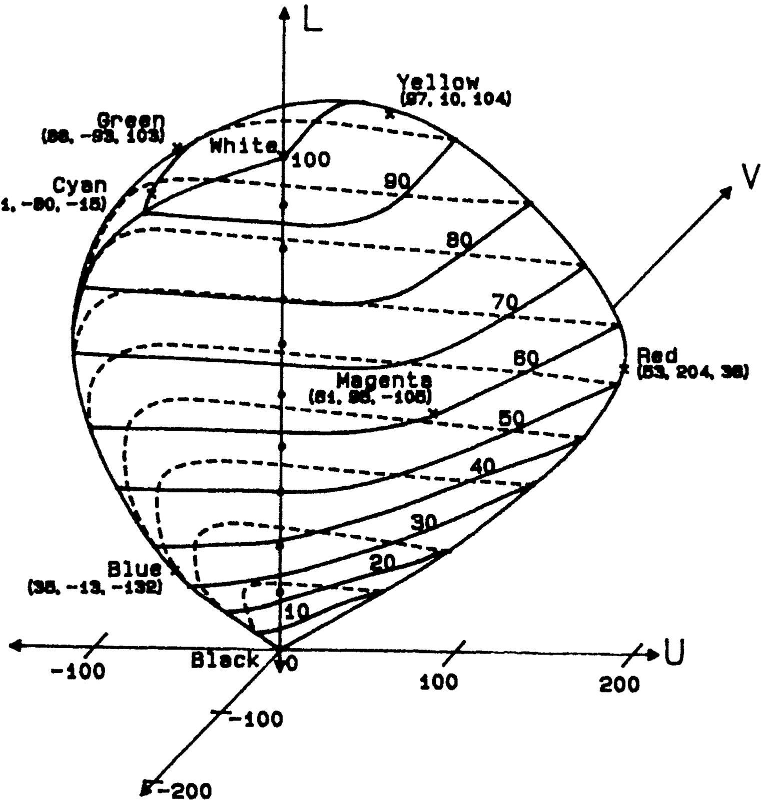


Figure 14 LUV colour space showing the boundaries of the RGB colour cube and the position of the basic colours (adapted from [5])

excellent exposition on this subject, while [16] discusses the use of uniform colour spaces for computer graphics.

3.5.2 RGB to LUV conversion

Before the formulas are discussed, it must be noted that the values of LUV are not in the [0,1] range. Each component has a different range, depending on the values chosen for the matrix P and the vector V. If P2 and V4 are used (see 3.1.2), L will range between 0 and 100, U between -93 and 204, and V between −132 and 104. The ranges could be changed to be positive integers, without loss of uniformity, by a constant being added. To improve on the resolution, each component can be multiplied by the same constant. This will still preserve uniformity.

GIVEN: R, G, and B, each in [0, 1]

DESIRED: L in [0, 100], U in [-93, 204], and V in [−132, 104], using P = P2 and V = V2 (see 3.1.2)

FORMULA:

LET

$$X = 0.437509R + 0.331566G + 0.179175B$$
$$Y = 0.205887R + 0.710498G + 0.0836149B$$
$$Z = 0.1421G + 0.931709B$$

$$u = \frac{4X}{X + 15Y + 3Z} \qquad v = \frac{9Y}{X + 15Y + 3Z}$$
$$u_0 = \frac{4X_0}{X_0 + 15Y_0 + 3Z_0} = 0.1978645$$
$$v_0 = \frac{9Y_0}{X_0 + 15Y_0 + 3Z_0} = 0.4694914$$
$$Y_0 = 1$$

THEN

$$L = 116\left(\frac{Y}{Y_0}\right)^{\frac{1}{3}} - 16 \qquad \text{if } \frac{Y}{Y_0} > 0.01$$
$$U = 13L(u - u_0)$$
$$V = 13L(v - v_0)$$

3.5.3 LUV to RGB conversion

The LUV to RGB conversion is simply the inverse of the RGB to LUV conversion. It must be noted, however, that not all the LUV values within the given ranges can be converted to be valid (that is in the [0,1] range) RGB values. This is due to the form of the RGB colour cube in the LUV colour space (see figure 14).

GIVEN: L in [0, 100], U in [-93, 204], and V in [−132, 104], using P = P2 and V = V2 (see 3.1.2)

DESIRED: R, G, and B, each in [0, 1]

FORMULA:

LET

$$Y = Y_0\left(\frac{L + 16}{116}\right)^3$$
$$X = \frac{9(U + 13u_0L)}{4(V + 13v_0L)}Y$$
$$Z = \left(\frac{39L}{V + 13v_0L} - 5\right)Y - \frac{X}{3}$$

where

$$Y_0 = 1$$
$$u_0 = \frac{4X_0}{X_0 + 15Y_0 + 3Z_0} = 0.1978645$$
$$v_0 = \frac{9Y_0}{X_0 + 15Y_0 + 3Z_0} = 0.4694914$$

THEN

$$R = 2.87574X - 1.25391Y - 0.440496Z$$
$$G = -0.848557X + 1.80318Y + 0.00135981Z$$
$$B = 0.129418X - 0.275013Y + 1.07309Z$$

NOTE:

Input is illegal if one of the following is false:

1. $L = 0 \Rightarrow U, V, R, G, B, = 0$
2. $V + 13v_0L = 0 \Rightarrow L = 0$
3. R, G, B in [0, 1]

3.5.4 Use of the LUV model

The LUV model is an approximation of a uniform colour space and is recommended by the CIE for use in colour difference evaluation. Unfortunately, it is still only an approximation. If a better uniform colour space model were to be defined, all the advantages of the LUV model would still hold for the new model since the LUV model's advantages stem from its uniformity, not from the LUV model as such.

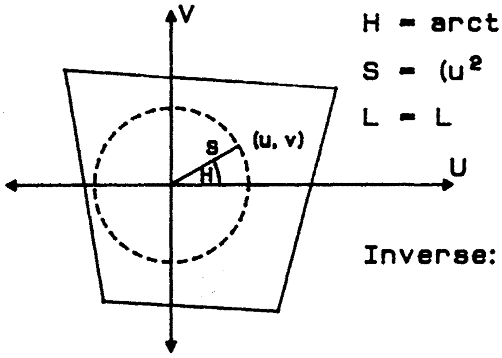
The LUV model is not very suitable for interactive applications. Its conversions are relatively slow (a cubic root must be computed), and it is difficult to acquire a "feeling" for the model, that is, to know where certain colours are located in the colour space.

Another disadvantage is the fact that each component of the LUV model has its own range. If R, G and B range between 0 and 1, L, U and V will range between 0 and 100, -93 and 204, and −132 and 104 respectively.

In order to provide a uniform colour space, the LUV model must be sensitive to environmental factors. This further complicates matters. External factors, such as the phosphors used in the colour display unit and the light source illuminating the display unit, all have an influence on the colours perceived by the human eye.

In spite of the disadvantages, the LUV model can be useful for uniform colour space applications, such as automatic colour assignment (see 4.4). An example is the assignment of colour to a vegetation DTM. Typically, one would want the different vegetation areas to be displayed with colours that are as different as possible. This could be done by spacing the colours as far as possible from one another in LUV space.

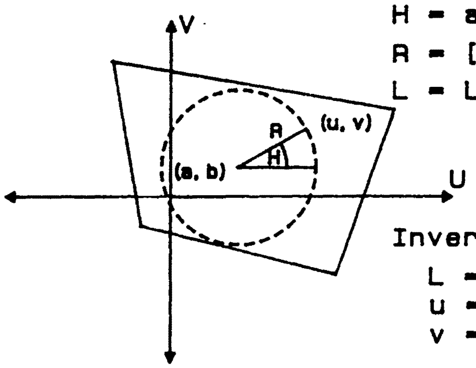
For a digital elevation model (showing the heights of an area) one would want the colours to show the increase in height. This may be done by selecting colours along a line in LUV space. If the intervals between the colours on the line are equal to one another, the height increase will be represented



$$H = \arctan\left(\frac{v}{u}\right)$$
$$S = (u^2 + v^2)^{\frac{1}{2}}$$
$$L = L$$

Inverse:
$$L = L$$
$$u = S\cos(H)$$
$$v = S\sin(H)$$

Fig 15
Definition of H, S and L in terms of the LUV colour model



$$H = \arctan\left(\frac{v-b}{u-a}\right)$$
$$R = [(u-a)^2 + (v-b)^2]^{\frac{1}{2}}$$
$$L = L$$

Inverse:
$$L = L$$
$$u = a + R\cos(H)$$
$$v = b + R\sin(H)$$

Fig 16
Definition of H, R and L with the center of the circle at (a, b)

uniformly. That is, small difference in colour will imply a small difference in height.

In [17] a natural, user-friendly way of specifying LUV colours along a curve is given. For a given L value the U and V components are specified in polar coordinates, called S (saturation) and H (hue) (see figure 15). L, S and H are similar to the HSL model, except that uniformity is preserved for each component. The advantages of this are obvious.

The size of the hue circle could be improved if centres other than (0,0) are used (figure 16). This will increase the colour space utilisation at the cost of saturation changes along the circumference of the hue circle.

If an image has to represent three input functions, the LUV model could be used, together with statistics on the input functions, to provide an "optimal" colour assignment [15]. Refer to 4.4 for more detail on this.

3.6 Choosing the Right Colour Model

The selection of a colour model depends on the intended application. An application where the user interactively specifies or changes colours may be best served by one of the HSI, HSL or CNS models. The CNS model allows the use of natural English names, but has a coarse resolution. The HSI and HSL models allow fine resolution and appear natural to the user. The HSI model corresponds to the artist's use of tint, shade and tone. The conversions needed for the HSI and HSL models are fast, and both models can be used in painting programs. Whether HSI and HSL should be used depends on whether the user wants the fully saturated colours to be at I = 1 (for HSI) or at L = 0.5 (for HSL).

For applications needing a uniform colour space, the LUV model is the obvious choice. It must, however, be remembered that the conversions needed for this model are slower than for the other models.

4. Colour Assignment

In this section it is assumed that the hardware used for colour display consists of a frame buffer and a colour lookup table (colour map or luvo). Each pixel in the frame buffer points to a location in the colour map that contains the colour description of the pixel. In this way the colours may be changed without the picture being changed. The size of the colour map is much less than that of the frame buffer. Typically, the frame buffer may have a size of 512 by 512, giving 262 144 pixels, while the colour map may have only 256 entries. These values will be used in the following discussion.

4.1 Displaying Multi-Image Pictures

The process of displaying digital multi-image pictures on the hardware described above can be seen as consisting of two steps, namely quantisation and colour assignment [18].

Quantisation is the process of assigning representation values to ranges of input values. For example, the 262 144 possible pixel values of the frame buffer must be limited to 256 — the size of the colour map — and all other pixel values must be mapped onto these 256 values. Colour assignment is then simply the assignment of representative colours to the colour map by using one of the colour models.

Typical applications where these steps are needed are: mapping of a video image with R,G,B components onto a k-sized colour map [16]; the false colouring of satellite images; and the combined display of several DTM's, such as DTM's of the soil type, vegetation and slope of an area.

A more formal description of the process of combining and displaying m input images is as follows (see also figure 17).

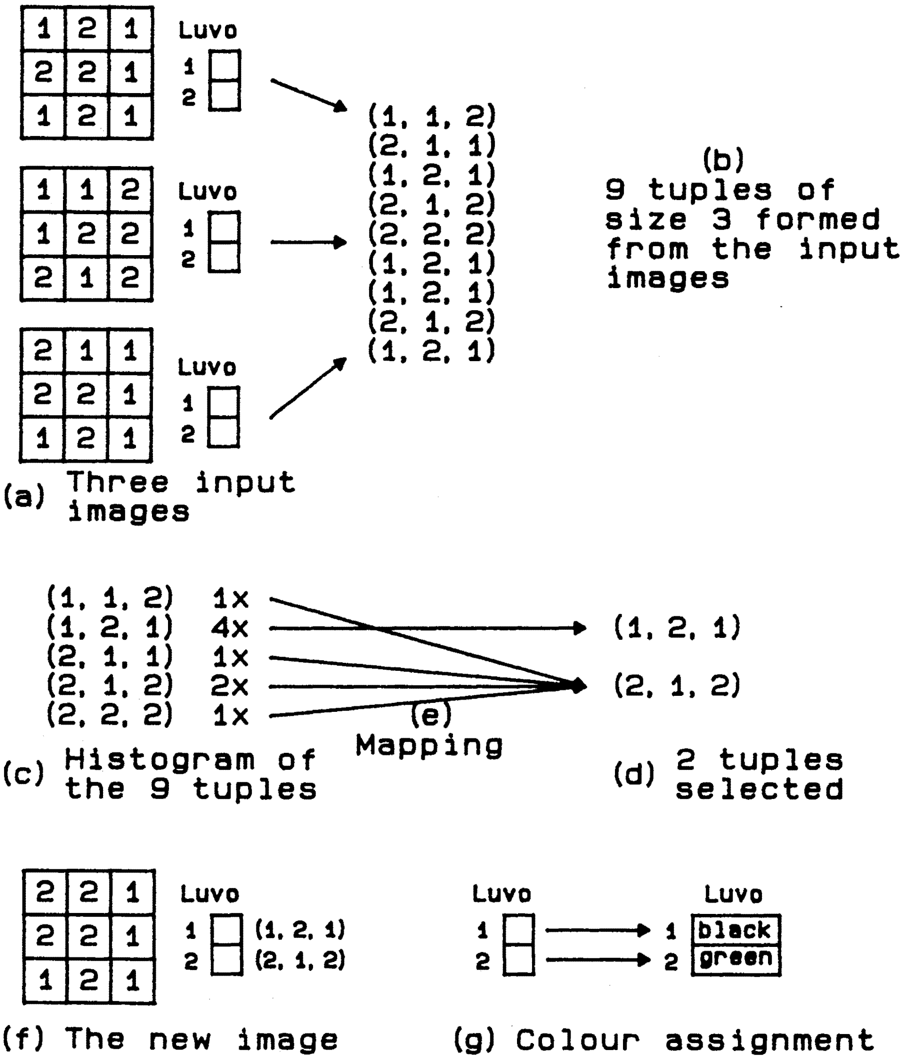


Figure 17 Combining 3 input images (size 3 x 3) into one

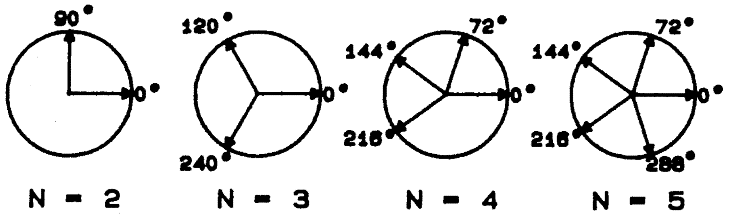


Figure 18 Polar coordinate system for N = 2, 3, 4 and 5

1. Input: Start with n tuples of size m, where a tuple consists of the m input values that have to be represented by one pixel in the final image.
2. Quantisation: Quantise the n tuples to k tuples, where k is the size of the colour map. This is done in three steps (see [18]):
    - (a) Obtain the distribution of the n tuples (a histogram of the tuples).
    - (b) Select k tuples based on the tuple distribution. Typically, select the k tuples that occurred most frequently.
    - (c) Map all the other tuples onto the k tuples selected in (b), and create a new image.
3. Colour assignment: Assign k colours to the k tuples by using the RGB, HSI, HSL or LUV model. Some of the more detailed requirements for this process might be:
    - (a) Use a set of colours with an easily remembered order, showing the order of the tuples.
    - (b) Select colours that are perceived as being as different as possible by the user.
    - (c) Ensure that the colours preserve the distance between the tuples.

4.2 Colour Assignment using the HSI Model

For multi-image pictures the colour of an entry in the colour map might be defined as a function of all the image components. For three or less image components a straightforward assignment of a colour component (hue, saturation or intensity) to an image component may be done. The RGB colour space may also be used in this way, but the use of the HSI colour space is said to give better results. This is evident if there is only one image component because the hue colour component has a large dynamic range. According to [6], about 128 hues can be distinguished by the human eye.

For two image components saturation is usually selected as the second colour component because most displays offer the smallest number of discernable steps along the intensity range. If colours differ only in saturation, we can distinguish from 16 (for yellow) to 23 (for red and magenta) colours. Three image components will use hue, saturation and intensity.

It is also possible to assign one colour component as a function of more than one image component. In this way more than three image components can be displayed at the same time. Some information will be lost because more than one set of image component values will be mapped onto the same colour, but such a multi-image colour picture can still be useful for four or five image components.

The colour assignment for two to five image components may be defined as follows [13]:

$$I = \max\{C_i\}$$

$$S = \frac{\max\{C_i\} - \min\{C_i\}}{\max\{C_i\}}$$

$$H = \arctan\left(\frac{\sum_{i=1}^{N} C_i \sin\theta_i}{\sum_{i=1}^{N} C_i \cos\theta_i}\right)$$

WHERE

N = number of image components ($2 \le N \le 5$)

C_i = value of image component i ($1 \le i \le N$)

θ_i = direction of component image axis in polar coordinate system (see fig. 18)

$$(\theta_1, \theta_2, \ldots \theta_i) = \begin{cases} (0°, 90°) & \text{if } N=2 \\ (0°, 120°, 240°) & \text{if } N=3 \\ (0°, 72°, 144°, 216°) & \text{if } N=4 \\ (0°, 72°, 144°, 216°, 288°) & \text{if } N=5 \end{cases}$$

For N = 3, the choice for the angles of the component axes corresponds to the primary colours. Arrangements where two component axes are directly opposite one another in the polar system are avoided as the two components will cancel one another, since $\sin(180 + k) = -\sin(k)$ and $\cos(180 + k) = -\cos(k)$.

4.3 Colour Assignment using the HSL Model

The colour assignment used for the HSI model may be adjusted for use with the HSL model. However, for the latter model the difference between the S and L colour components may not be as obvious as with the HSI model. If there are two image components that are assigned directly to a colour component, the H and L components may be preferred to the H and S components. This is because L offers a wide range, going from black through the pure colour to white.

If a colour component is assigned as a function of more than one image component, the assignment will be as follows:

$$L = \frac{\max\{C_i\} + \min\{C_i\}}{2}$$

$$S = \begin{cases} \dfrac{\max\{C_i\} - \min\{C_i\}}{\max\{C_i\} + \min\{C_i\}} & \text{if } L \leq 5 \\ \dfrac{\max\{C_i\} - \min\{C_i\}}{2 - \max\{C_i\} - \min\{C_i\}} & \text{if } L > 5 \\ 0 & \text{if } L = 0 \text{ or } L = 1 \end{cases}$$

$$H = \arctan\left(\frac{\sum_{i=1}^{N} C_i \sin\theta_i}{\sum_{i=1}^{N} C_i \cos\theta_i}\right)$$

WHERE

N = number of image components ($2 \leq N \leq 5$)

C_i = value of image component i ($1 \leq i \leq N$)

θ_i = direction of component image axis in polar coordinate system (see fig. 18)

$$(\theta_1, \theta_2, \ldots \theta_i) = \begin{cases} (0°, 90°) & \text{if } N=2 \\ (0°, 120°, 240°) & \text{if } N=3 \\ (0°, 72°, 144°, 216°) & \text{if } N=4 \\ (0°, 72°, 144°, 216°, 288°) & \text{if } N=5 \end{cases}$$

The definitions of S and L differ from the HSI assignment, while the H component is exactly the same.

4.4 Colour Assignment using the LUV Model

In a manner similar to that for the HSI and HSL colour models, colour assignment in LUV space may be done by the assignment of L, U and V to each of the three image components. In the LUV space the axis offering the greater colour variation lies along the U axis (that is, green to red) while the least variation is found along the L axis (black to white). If this colour assignment is used, some problems may arise because even if the individual values of L, U and V are within the specified limits, the point they represent in LUV space may be outside the limits. This is because of the form of the RGB colour cube in LUV space (see figure 14).

If there is only one image component, colours may be assigned by going along a line (or circle, or some similar shape) in LUV space. If the colours are assigned at regular intervals along the line, the colours should appear to be equidistant to the human eye (because of the uniformity of LUV). For two image components a plane (or other geometric figure) in LUV space has to be used.

A method for assigning LUV colours to an image with three components is given in [15]. This method uses statistics on the distribution of the image components' values. A transformation that will fit the component space "optimally" into the LUV colour space is deduced. The formulas used are as follows:

GIVEN:

$$\begin{bmatrix} \bar{L} \\ \bar{U} \\ \bar{V} \end{bmatrix} = \begin{bmatrix} 58.1135 \\ 21.9842 \\ -5.7558 \end{bmatrix}$$ = mean values of regular samples in the displayable LUV space (using D65 for the 1984 observer).

$$\begin{bmatrix} d_{01} \\ d_{02} \\ d_{03} \end{bmatrix} = \begin{bmatrix} 50.5489 \\ 46.6821 \\ 18.6878 \end{bmatrix}$$ = standard deviations of the samples in LUV space in decreasing order.

$$R_0 = \begin{bmatrix} 0.157303 & 0.0857109 & 0.983824 \\ -0.884021 & 0.456285 & 0.101593 \\ 0.440185 & 0.885696 & -0.147548 \end{bmatrix} =$$ matrix such that each column is a normalised eigenvector of the covariance matrix for the displayable LUV space. The eigenvectors are ordered such that their eigenvalues are in decreasing order.

Set of (f_1, f_2, f_3) triples. formed by the three image components f_1, f_2, and f_3.

DESIRED:

The (L, U, V) triple corresponding to (f_1, f_2, f_3), using a data dependent conversion that does not preserve distances.

FORMULA:

As above, calculate the following for the $f_1 f_2 f_3$ space:

$$\begin{bmatrix} \bar{f_1} \\ \bar{f_2} \\ \bar{f_3} \end{bmatrix}$$ = mean distribution. $$\begin{bmatrix} d_1 \\ d_2 \\ d_3 \end{bmatrix}$$ = standard deviation

R = matrix of normalised eigenvectors similar to R_0, but for this space (inverse is R^{-1}).

The conversion is given by:

$$\begin{bmatrix} L \\ U \\ V \end{bmatrix} = R_0 \begin{bmatrix} \frac{d_{01}}{d_1} & 0 & 0 \\ 0 & \frac{d_{02}}{d_2} & 0 \\ 0 & 0 & \frac{d_{03}}{d_3} \end{bmatrix} R^{-1} \begin{bmatrix} f_1 - \bar{f_1} \\ f_2 - \bar{f_2} \\ f_3 - \bar{f_3} \end{bmatrix} + \begin{bmatrix} \bar{L} \\ \bar{U} \\ \bar{V} \end{bmatrix}$$

To preserve distances, replace the $\frac{d_{0i}}{d_i}$ values with their minimum.

5. Guidelines for Effective Colour Use

The following guidelines are based on [2] (see also [19] and [20]) with some remarks added from own experience. The guidelines are listed according to their area of derivation physiological, perceptual, or cognitive.

5.1 Physiological Guidelines

Avoid the simultaneous display of highly saturated, spectrally extreme colours. It is said that extreme colour pairs, such as red and blue or yellow and purple, should be avoided since they cause frequent refocusing and visual fatigue. This strain on the eye is not always felt immediately, but may show itself in the long run. However, desaturation of spectrally extreme colours or the reduction of their intensity will reduce the need for refocusing.

Avoid pure blue for text, thin lines, and small shapes. Our visual system cannot deal adequately with detailed, sharp, short-wavelength stimuli. However, blue does make a good background colour and is perceived clearly out into the periphery of our visual field.

Avoid adjacent colours differing only with regard to the amount of blue. Edges that differ only with regard to the amount of blue will appear indistinct. This is especially visible in the blue-green and yellow-white (where blue is added) regions.

Older viewers need higher levels of brightness to distinguish colours.

Colour changes appearance as ambient light level changes. Displays change colour under different kinds of ambient light — fluorescent, incandescent, or daylight. Appearance also changes as the light level is increased or decreased. On the one hand, a change is due to increased or decreased contrast, and on the other, it is due to a shift in the eye's sensitivity. The background colour of a display has similar effects.

The magnitude of a detectable change in colour varies across the spectrum. Small changes in hue are more detectable in yellow, magenta and cyan-blue than in green and the extreme reds and purples. Small changes in saturation are more difficult to detect in yellow, green and blue than in red-yellow, cyan-blue and blue-magenta. Intensity changes are more visible in green and yellow than in blue.

Difficulty in focusing results from edges created by colour alone. Our visual system depends on a difference in brightness at an edge to effect clear focusing. Therefore, multi-coloured images should be differentiated on the basis of brightness as well as of colour.

Avoid red and green in the periphery of large-scale displays. Owing to the insensitivity of the retinal periphery to red and green, these colours should be avoided in saturated form, especially for small symbols and shapes. Blue and especially yellow are good peripheral colours.

Opponent colours go together well. Red and green or yellow and blue are good combinations for simple displays. The opposite combinations — red with yellow or green with blue — produce poorer images.

For colour-deficient observers, avoid single-colour distinctions.

5.2 Perceptual Guidelines

Not all colours are equally discernible. Perceptually, we need a large change in wavelength to perceive a colour difference in some portions of the spectrum and a small one in other portions. Colour differences are perceived more readily in the yellow-red, cyan-blue and blue-magenta colour regions.

Luminance does not equal brightness. Two colours of equal luminance but different hue will probably appear to be of differing brightness. The deviations are most extreme for colours towards the ends of the spectrum (red, magenta, blue).

Different hues have inherently different saturation levels. Yellow in particular always appears to be less saturated than other hues.

Lightness and brightness are distinguishable on a printed hard copy, but not on a colour display. The nature of a colour display does not allow lightness and brightness to be varied independently (see 2.1 for the definition of these terms).

Not all colours are equally readable or legible. Extreme care should be exercised with text colour relative to background colours. In addition to causing a loss in hue with reduced size, inadequate contrast frequently results when the background and text colours are similar. As a general rule, the darker, spectrally extreme colours such as red, blue magenta, brown, etc., make good backgrounds while the brighter, spectrum-centred, and desaturated hues produce more legible text.

Hues change with intensity and background colour. When grouping elements on the basis of colour, ensure that backgrounds or nearby colours do not change the hue of an element in the group. Limiting the number of colours and ensuring that they are widely separated in the spectrum will reduce confusion.

Avoid the need for colour discrimination in small areas. Hue information is lost in small areas. In general, two adjacent lines of a single-pixel width will merge to produce a mixture of the two. Also, the human visual system produces sharper images with achromatic colours. Thus, for fine detail, it is best to use black, white, and grey, while chromatic colours should be reserved for larger panels or to attract attention.

5.3 Cognitive Guidelines

Do not overuse colour. The best rule is probably to use colour sparingly. The benefits of colour as an attention getter, information grouper, and value assigner are lost if too many colours are used. Cognitive scientists have shown that the human mind experiences great difficulty in maintaining more than five to seven elements simultaneously; so it is best to limit displays to about six clearly discriminable colours when a definite meaning is associated with each colour. In some applications, such as where different shades of the same colour is used, this rule does not apply.

Be aware of the nonlinear colour manipulation in video and hard copy. Video or hard-copy systems cannot match human perception and expectations in all respects.

Group related elements by using a common background colour. Cognitive science has advanced the notion of set and preattentive processing. In this context, you can prepare the user for related events by using a common colour code. A successive set of images can be shown to be related by the use of the same background colour.

Similar colours connote similar meanings. Elements related in some way can convey the relationship by means of the similarity of their hues. The colour range from blue to green is experienced as being more similar than that from red to green. The saturation level can also be used to connote the strength of relationships.

Brightness and saturation draw attention. The brightest and most highly saturated area of a colour display immediately draws the viewer's attention. Yellow and green are good examples of this.

Link the degree of colour change to event magnitude. As an alternative to bar charts or tic marks on amplitude scales, displays can portray magnitude changes with progressive steps of changing colour. A desaturated cyan can be increased in saturation as the graphed elements increase in value. Progressively switching from one hue to another can be used to indicate passing critical levels.

Order colours by their spectral position. To increase the number of colours on a display requires that a meaningful order be imposed on the colours. The most obvious order is that provided by the spectrum with the mnemonic ROY G. BIV (red, orange, yellow, green, blue, indigo, violet). This is the same as the hue range of the HSI and HSL colour models.

Warm and cold colours should indicate action levels. Traditionally, the warm (long wavelength) colours are used to signify action or the requirement of a response. Cool colours, on the other hand, indicate status or background information. Most people also experience warm colours such as red as advancing toward them, hence forcing attention, and cool colours such as blue as receding or drawing away.

Do not mix the decorative use of colour with planned colour cueing. The logical side of our brain looks for meaning in the use of colour and will get tired and frustrated if none could be found [20].

The three-dimensional appearance of objects can be enhanced by the use of variations in the degree of saturation and/or intensity. Foreground colours are commonly rendered in bright colours and the background colours progressively reduced in saturation (or intensity) as the distance from the front increases [19].

6. Conclusion

While these guidelines offer some suggestions, they should certainly not be taken as binding under all circumstances. There are too many variables in colour display, colour copying, human perception, and human interpretation for any hard and fast rules to apply at all times, thus leaving open the way for experimentation.

References

[1] R. Shoup, [1979], Color Table Animation, *Computer Graphics*, **13** (2), 8 - 13.

[2] G.M. Murch, [1985], Colour Graphics Blessing or Ballyhoo?, *Computer Graphics Forum*, **4**, 127 - 135.

[3] G.S. Ellis, [1983], SCRAP Gebruikershandleiding, Special Report SWISK 29, NRIMS, CSIR, South Africa.

[4] P.P. Roets, [1983], IKSP (Ikonas Support Package), Internal Report 1524, NRIMS, CSIR, South Africa.

[5] D. Judd and G. Wyszecki, [1975], *Color in Business, Science and Industry*, John Wiley and Sons, New York.

[6] J.D. Foley and A. van Dam, [1983], *Fundamentals of Interactive Computer Graphics*, Addison-Wesley Publishing Company, USA.

[7] A.R. Smith, [1978], Color Gamut Transform Pairs, *Computer Graphics*, **12** (3), 12 - 19.

[8] G.H. Joblove and D.P. Greenberg, [1978], Color Spaces for Computer Graphics, *Computer Graphics*, **12** (3), 20 - 27.

[9] Status Report of the Graphics Standards Committee, *Computer Graphics*, **13** (3), 1979, III-37 - III-39.

[10] B. Meier, [1985], BUCOLIC : A Program for Teaching Color Theory to Art Students, *IEEE Computer Graphics and Applications*, 57 - 65.

[11] A.R. Smith, [1979], Tint Fill, *Computer Graphics*, **13** (2), 276 - 283.

[12] K.R. Sloan and C.M. Brown, [1978], Color Map Techniques, *Computer Graphics and Image Processing*, **10**, 297 - 317.

[13] W. Fink, [1976], Image Transformations Facilitating Visual Interpretation, Goddard Space Flight Center, Greenbelt, Maryland, June.

[14] T. Berk, L. Brownston, and A. Kaufman, [1982], A New Color-Naming System for Graphics Languages, *IEEE Computer Graphics and Applications*, 37 - 44.

[15] J. Tajima, [1983], Uniform Color Scale Applications to Computer Graphics, *Computer Vision, Graphics, and Image Processing*, **22** (1), 305 - 325.

[16] G.W. Meyer and D.P. Greenberg, [1980], Perceptual color spaces for computer graphics, *Computer Graphics*, **14** (3), 254 - 261.

[17] P.K. Robertson and J.F.O. O'Callaghan, [1986], The Generation of Color Sequences for Univariate and Bivariate Mapping, *IEEE Computer Graphics and Applications*, **6** (2), 24 - 32.

[18] P. Heckbert, [1982], Colour Image Quantization for Frame Buffer Display, *Computer Graphics*, **16** (3), 297 - 305.

[19] J.R. Truckenbord, [1981], Effective use of color in computer graphics, *Computer Graphics*, **15** (3), 83 - 90.

[20] H.J. Ehlers, [1985], The use of colour to help visualize information, *Computers and Graphics*, **9** (2), 171 - 176.

BOOK REVIEW

Effective Computer Applications

by Peter Pirow, 1986, Woodacres Publishers, 230 pages, ISBN 0 620 09323 4

Dr. Peter Pirow has made a most original and sorely needed longitudinal, case-history research contribution to the cost-effectiveness of business information systems in particular, and to the study of the social use of computers in general. *Effective Computer Applications* reflect a massive research effort spanning a 28 year period, incorporating a selection of 857 case studies in South Africa over an astonishing variety of applications and organisations. The extensive case study empirical data base was subjected to diversified hypothesis testing to determine various socio-economic and technical facets of computer system performance effectiveness. This carefully crafted work, including a wide-ranging general history of information and computers, and a special history of computer developments and applications in South Africa, is a remarkable intellectual tour de force and an exemplary, interdisciplinary scholarly task.

Voluminous descriptive statistics are presented, highlighting case history population parameters and characteristics, and quantitative measures of computer system success and failure. Numerous statistical tests are made of leading hypotheses and organisational performance measures culled from the scientific literature, with additional hypotheses and models from Dr. Pirow's research. These statistics include parametric, non-parametric, correlational and multivariate techniques appropriate for the empirical samples. The longitudinal quantitative analyses over almost a three-decade time period is clearly a major contribution to the world literature in business information systems. The case history and quantitative methodology is of great value, and I felt that it should have been explicated more fully for applied scientific practitioners, particularly in connection with empirical reliability and validity of the various measures of performance effectiveness.

The book concludes with a thoughtful analysis of the complex reasons why so many information systems fail and others succeed in various organisational contexts. Dr. Pirow particularly singles out the massive impact of computer illiteracy on system failures, and provides broad educational recommendations for achieving "computeracy" at the national level. He ends on a fitting sober, scientific note that the proverbial wisdom appearing in newspapers, magazines, and articles, based on "expert" opinion as to what works and what does not work in computer systems, "can only be tested by means of a study of a substantial number of applications", as he has done in this monumental work.

Hal Sackman, *School of Business, California State University*

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[3] S. Ginsburg, [1966], *Mathematical Theory of Context-free Languages,* McGraw Hill, New York.

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